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PROBLEMS ASSOCIATED WITH NOISE MEASUREMENTS IN AIRFLOWS

R. Gamba

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16. Abstract

Studies of the interrelation of turbulent pressure and velocity fluctuations at a given point in a flow performed by Nakamura et al. (1969) are shown to lead to a formal analogy between sound pressure waves and 'pseudowaves' of turbulent pressure. A review of recent research on the response of a microphone placed in a silent laminar airflow reported by Gamba (1973) is then followed by a discussion of the problem of estimating the noise within a flow on the basis of external noise measurements.

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PROBLEMS ASSOCIATED WITH NOISE MEASUREMENTS IN AIRFLOWS

R. Gamba*

ABSTRACT. In a survey of the principal known works that treat such problems, one of particular importance is an article by Akira Nakamura that appeared in 1969 in the Journal of the Acoustical Society of America, in which, after proposing and experimentally verifying a theoretical expression relating turbulent pressure fluctuations and turbulent velocity fluctuations at the same flow point, the author then establishes a formal analogy between acoustic pressure waves and turbulent "pseudo-pressure waves".

We then present the results of the work that was carried out in collaboration with the Research and Study Center of Toulouse and the E.B.M. research group (Toulouse) to determine the response of a microphone placed in a noiseless laminar air flow. As a first approach to the problem, we estimate the noise for interior flow by measuring the exterior flow noise. For fixed velocity, the output level of the microphone placed in the wind is given as a function of frequency, and we notice some important spectral differences at high frequencies between our results and those of Bruel and Kjaer. Nevertheless, we find that the total noise level as a function of velocity is in good agreement with that found by Bruel and Kjaer.

Since the results obtained are encouraging, we propose an improved version of the method to investigate interior flow noise.

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*Paul Sabatier University, Toulouse. Fourth Symposium on Aeronautical Acoustics.

Introduction

We have undertaken a preliminary study whose purpose is to determine the response of a microphone immersed in a noiseless laminar airflow, and to develop a method of measuring noise in the presence of wind. We intend here to present an account of what has appeared to us to be the most interesting items in the bibliography that we consulted, and to describe the experiments that we have worked on, thereby pointing the way for future work. /1*

When noise measurements are made well inside the region of fluid flow (air-conditioning ducts, for example, or perhaps measurements made outside in the presence of wind, even if it is "very light"), it is very quickly realized that the reading of the sonometer is purely indicative, and indeed may often be quite meaningless, so that interpretative readings are extremely hazardous.

There is no difficulty in understanding how a microphone sensitive to pressure variations about the mean value of pressure will be sensitive to all pressure variations, regardless of origin. Now, at a point of fluid flow, fluctuations in pressure may be distinguished as:

— acoustic;

— turbulent.

For turbulent pressure variations, it is possible to distinguish further between those which would exist in the absence of the microphone and those which are created by the presence of this microphone in the flow path.

If it is desired to measure noise by means of a microphone placed in the air flow, it is then necessary to treat spearately the acoustic pressure and the other pressure fluctuations. To do this,

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*Numbers in margin indicate pagination in original foreign text.

we can either do something physical (this is the role of the anti-wind screens) or else devise a measurement technique that makes it possible to deal with individual parameters.

Survey of Principal Known Works

The work of Bruel and Kjaer

In bibliographies prior to 1960, we find only an assortment of quite different experiments whose aim was to calculate the noise attenuation that was effected by an anti-wind screen. Moreover, these results cannot be compared with one another because the experimental conditions were not adequately defined.

By contrast, the work carried out by Bruel and Kjaer (published in the Technical Review, Bruel and Kjaer, 1960, No. 2) is deserving of a brief review.

The purpose was to measure the noise induced by an air current blowing (at different velocities) against a type 4131 condenser microphone, which may or may not be provided with an anti-wind protective grid. Bruel and Kjaer have chosen, in order to produce a noiseless flow, the following three experimental set-ups:

— for velocities less than 40 km/hr, the runs were carried out by means of a "turn-stile" device (Figure 1) driven by a low-noise motor, with the arm supporting the microphone having an aerodynamic form;

— for velocities in the range between 40 and 120 km/hr, the microphone was mounted on a vehicle (Figure 2). The measurements were made with the motor off, and in the absence of wind and other vehicular traffic; /3

— for higher velocities (130, 140, and 195 km/hr), an airplane was used (Figure 3). There also, measurements were made with the motor off.

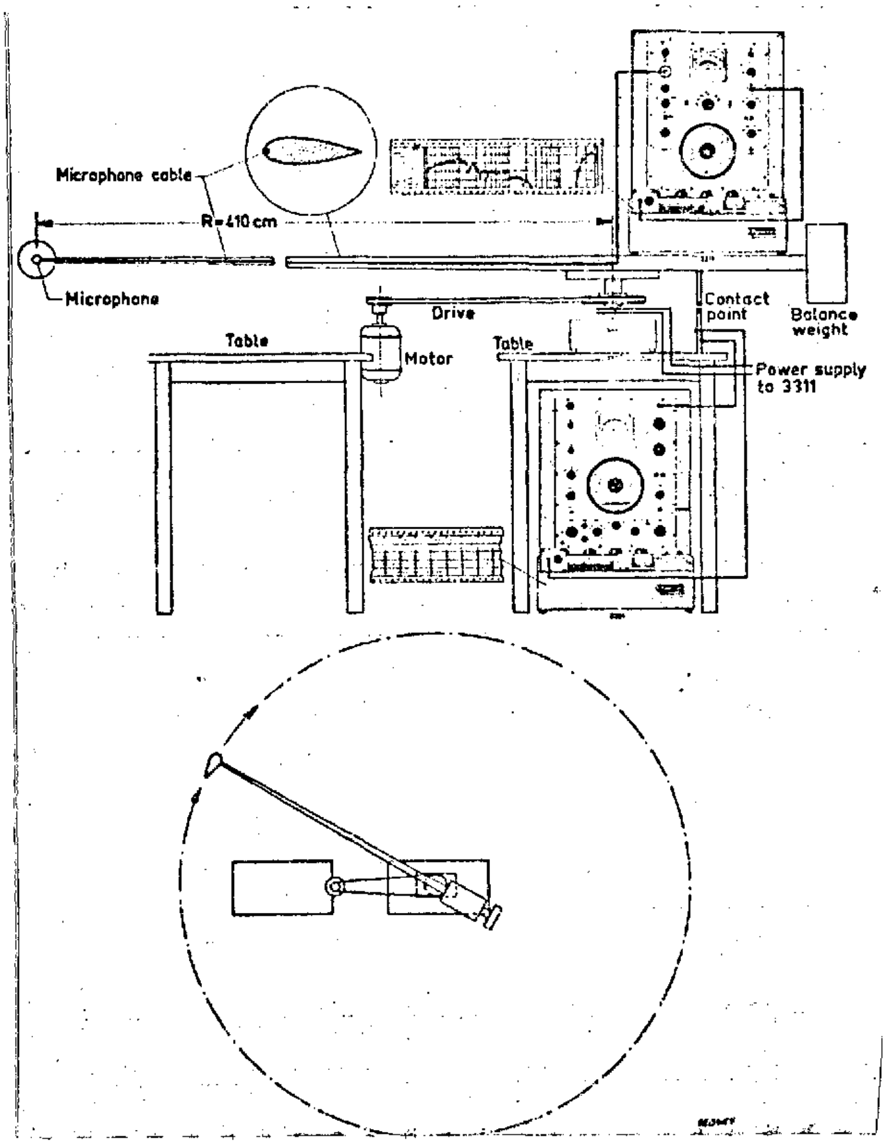


Figure 1.

In the three cases, an analysis by 1/3 octave frequency bands was carried out. Figure 4 shows the total noise level in the frequency bandwidth 20 - 20,000 Hz as a function of velocity. /4

The work of Nakamura

Among the publications that have appeared in the course of the last ten years, that of Nakamura has the advantage, by virtue of its simplicity, of clarifying the physical phenomena that involve the transducer; for that reason, we have chosen to discuss it here.

a) Expression for turbulent pressure fluctuations

We have said that right in the middle of the flow region there coexisted the turbulent pressure fluctuations and the fluctuations of sound pressure. If the average flow velocity is small compared with the velocity of sound, it is possible to regard the former as being associated with the average flow velocity, while the latter propagate at the speed of sound.

It must be acknowledged that these two pressure fields coexist without any interaction

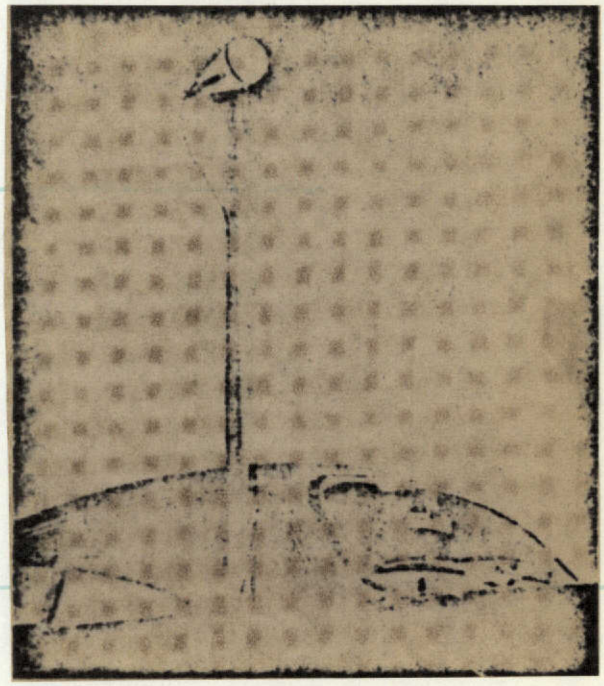
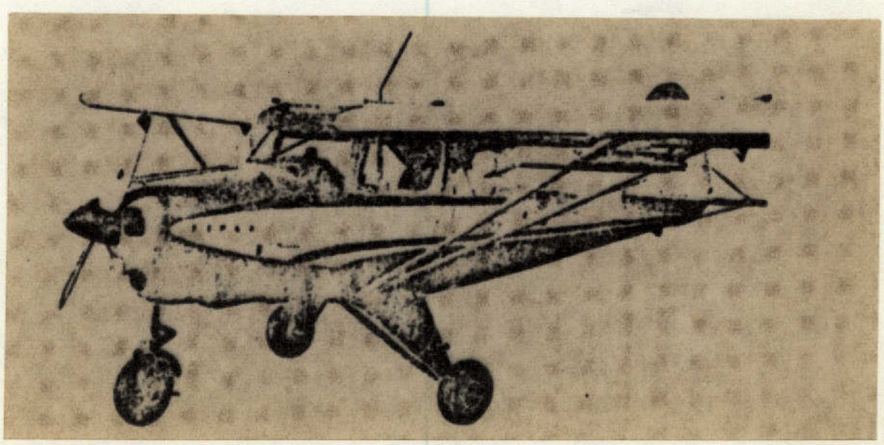


Figure 2.



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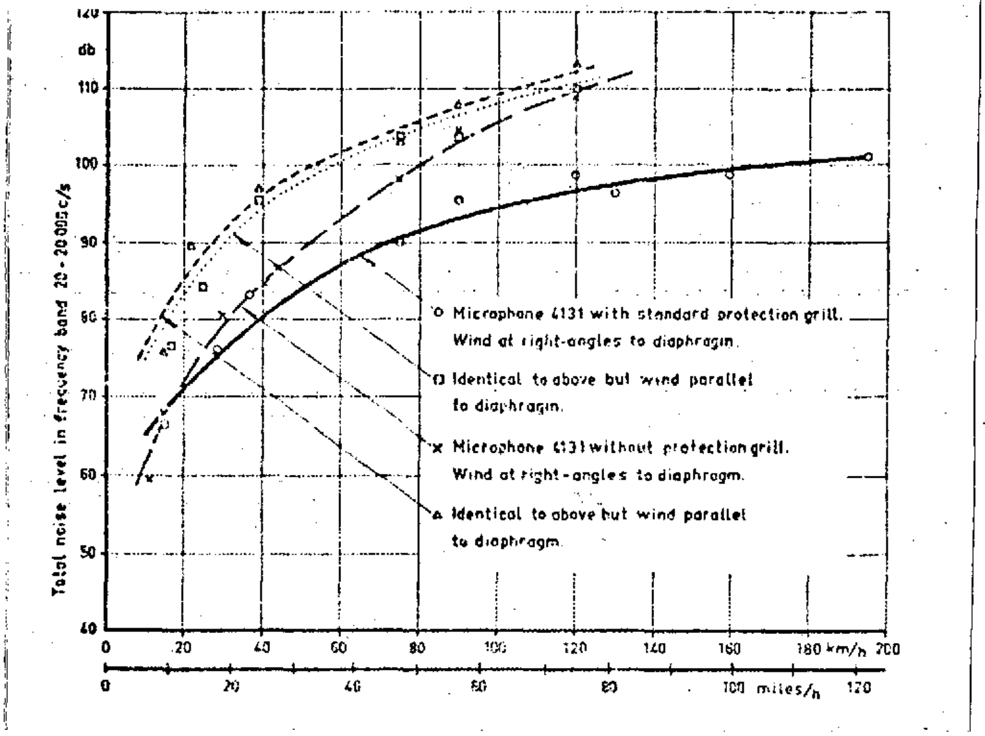


Figure 4.

energy, which is justified if the sound energy is small compared with the flow energy. /5

The expression for the pressure fluctuations caused by flow turbulence is deduced from the following propositions:

(1) the acoustic pressure level is negligible compared with the level of pressure fluctuations due to turbulence;

(2) the velocity fluctuations are small compared to the average flow velocity (i.e., the intensity of the turbulence is weak);

(3) the direction of the average velocity is independent of time, and the direction of the instantaneous velocity is equally well taken to be independent of time.

Let us consider a quasi-stationary tube of flow, that is, one such that $\partial V_0/\partial t \equiv 0$, and $V = V_0 + V'$ with $V' \ll V_0$ and $V \neq V_0$.

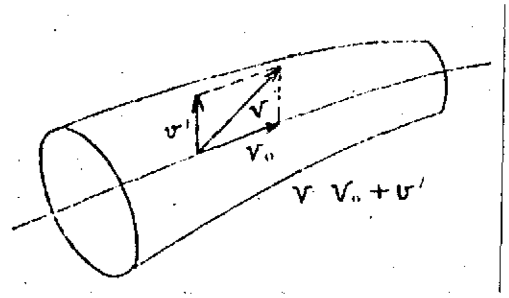


Figure 5.

For a tube of flow in the steady state, one can write:

$$\frac{1}{2} V^2 + \frac{P}{\rho} = K \quad (K = \text{const and } \rho = \text{const}).$$

By replacing V by $V_0 + V'$, and P by $P_0 + P'$, we have:

$$\frac{1}{2}(V_0 + V')^2 + \frac{P_0 + P'}{\rho} = K$$

$$\frac{1}{2} V_0^2 + \frac{P_0}{\rho} + \frac{P'}{\rho} + V_0 V' = K$$

neglecting second order terms. ~~Ho~~.
However,

$$\frac{1}{2} V_0^2 + \frac{P_0}{\rho} = K \Rightarrow$$

$$\frac{P'}{\rho} + V_0 V' = 0$$

$$P' = -\rho V_0 V'$$

so that, by taking the square of the average value:

$$P'^2 = +\rho^2 V_0^2 v'^2 \Rightarrow \overline{P'^2} = \rho^2 V_0^2 \overline{v'^2}$$

$$\Rightarrow \sqrt{\overline{P'^2}} = \rho V_0 \sqrt{\overline{v'^2}}$$

that is: /6

$$\boxed{(P')_{rms} = \rho V_0 (v')_{rms}}$$

Thus, by measuring the average velocity V_0 at a given point, and the effective value $(v')_{eff}$ of the velocity fluctuation, we can deduce, within the framework of the stated hypotheses, the effective value $(P')_{eff}$ of the pressure fluctuation. This demonstration, beguiling in its simplicity, may appear to some to be on shaky grounds. Indeed, Bernoulli's theorem is applicable only to a thin stream in steady state fluid flow; in the case that concerns us, there is no steady state flow, and we can no longer speak of such a thin stream. Nevertheless, the lack of rigor in this exercise is not very disturbing, since Nakamura has made an experimental verification to very good accuracy.

b) Experimental results

These have been obtained in a wind tunnel for which the schematic diagram is given below.

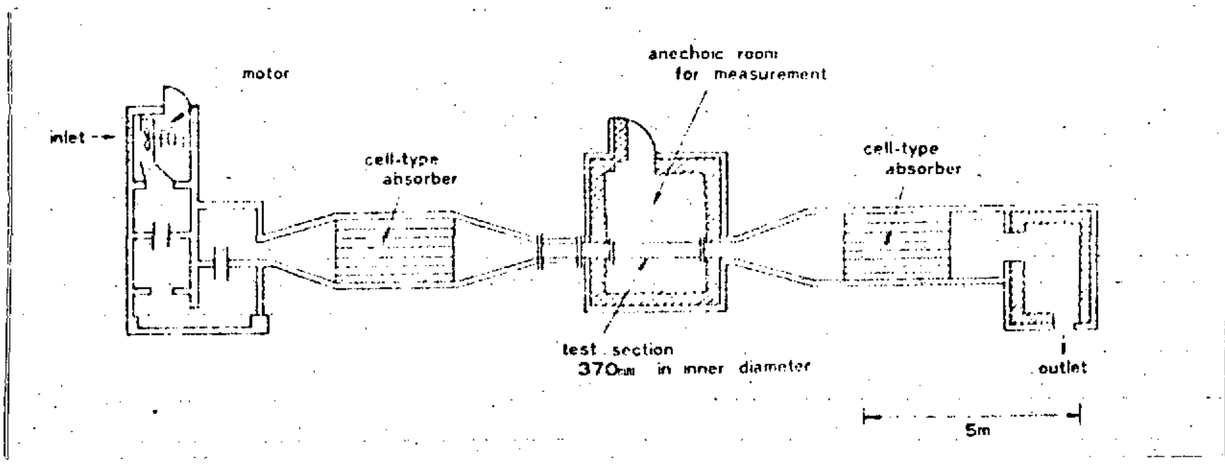


Figure 6.

The conditions of the experiment were as follows:

— average flow velocity, V_0, on the order of 10 m/s;

— ambient acoustic pressure level, less than 50 dB (Re $2 \cdot 10^{-5}$ p_a);

— turbulent intensity ($I = \frac{\sqrt{\overline{v'^2}}}{V_0}$), less than 1% for each 1/3 octave, and less than 4% for all frequencies. /7

The measurements were made with two condenser microphones stripped of their protective grid, with the diaphragm placed perpendicular to the wind direction.

We used the Bruel and Kjaer microphones, model 4131 (one inch diameter) and model 4133 (1/2 inch diameter).

A probe microphone has likewise been used, with its axis parallel to the wind direction.

The average velocity and the turbulence were measured with a DISA constant-temperature hot-wire anemometer, model 55.A.22.

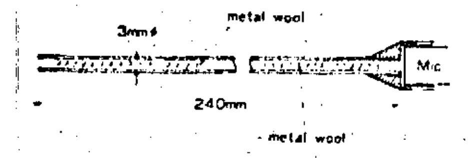


Figure 7.

If the diaphragm of the microphone is excited only by pressure variations due to turbulence, then the value of these variations will be indicated by the output signal of the microphone, and will be expressed in terms of acoustic pressure level in decibles [by the relationship $N_{dB} = 10 \log \left(\frac{P'}{Po}\right)^2$, where $Po = 2.10^{-5}Pa$, and P' is the pressure variation to be measured], according to the sensitivity of the microphone. This sensitivity will have to take account of the acoustic response of the probe (if used). Indeed, if there is no flow past the probe, the pressure variations of the probe entrance will propagate up to the microphone as sound waves. Figure 8 shows that the experimental results obtained with the microphone in conjunction with the probe are in good agreement with the calculation of P'_{eff}, according to the formula $P'_{eff} = \rho V_0 (v')_{eff}$. For this experiemnt, V_0 was varied from 3 to 10 m/s.

Figure 9 shows the differences between the output signals of the probe, the 1-inch microphone, and the 1/2-inch microphone. The solid line indicates the value of $P' = \rho V_0 v'$, calculated on the basis of the measured value of v'.

We see that the output level of the probe is in good agreement with the calculated value up to about 1000 Hz. On the other hand, /8

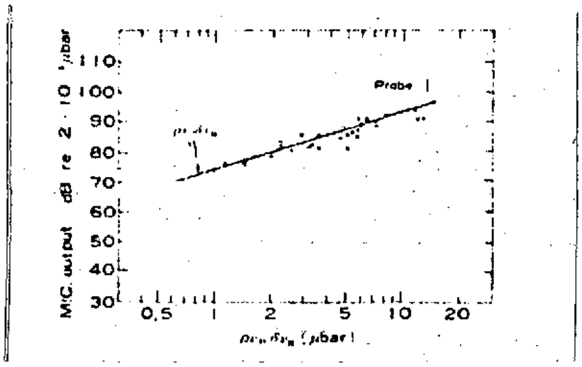


Figure 8.

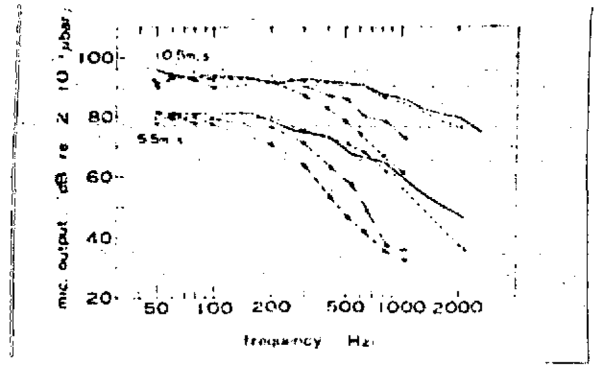


Figure 9.

the responses of the one-inch and 1/2-inch microphones depart from the calculated value for frequencies above some particular value.

This frequency f_e, beyond which the deviation becomes appreciable, is an increasing function of average velocity V_0 and a decreasing function of the diameter of the microphone. Table 1 gives the values of f_e and V_0/f_e for different values of V_0 and for the two microphones. Although the reading of f_e on the experimental curves is rather crude, it is possible to determine that V_o/f_e is invariant for a given microphone. Moreover, we note that the average value of V_0/f_e is roughly equal to twice the diameter of the particular microphone.

TABLE 1.

Mean flow velocity	½-in.-diam microphone		1-in.-diam microphone	
m/sec	f_e Hz	v_0/f_e $(=\lambda_e)$ cm	f_e Hz	v_0/f_e $(=\lambda_e)$ cm
3.81	...	...	...	...
4.64	200	2.3	80	5.8
5.55	200	2.8	100	5.6
6.58	300	2.2	100	6.6
7.54	300	2.5	100	7.5
8.34	300	2.8	200	4.2
9.68	300	3.2	200	4.8
10.65	300	3.6	200	5.3
11.49	400	2.9	300	3.8
	average	2.8	*average*	5.4

c) Interpretation of the results and the analogy with sound waves

There is physical significance to the fact that $V_0/f = \lambda$ is the apparent wavelength of the fluctuation of frequency f carried along by the fluid at the velocity V_0. We see, therefore, a formal analogy between acoustic waves (propagating at the speed of sound c) and "pseudo-pressure waves" due to turbulence (Table 2).

TABLE 2.

	Pressure fluctuation	Wavelength	Impedance
Acoustic waves	$P_a = \rho c u$	$\lambda = \frac{c}{f}$	$Z_a = \rho c$
Pseudo-flow waves	$P' = \rho V_o v'$	$\lambda_e = \frac{V_o}{f}$	$Z_e = \rho V_o$

u = acoustic vibration velocity, Pa = acoustic pressure

In these relationships we can conclude: /9

$$\lambda_e = \left(\frac{V_o}{c}\right)\lambda \quad \text{and} \quad Z_e = \left(\frac{V_o}{c}\right) Z_a$$

Furthermore, if $v' = u \Rightarrow P' = \left(\frac{Vo}{c}\right) Pa$

then, $P' = Pa \Rightarrow v' = \left(\frac{c}{Vo}\right) u$

If $Vo \ll c$, then $\lambda_e \ll \lambda$ and $Ze \ll Za$.

Furthermore, if $v' = u \Rightarrow P' \ll Pa$

or if $P' = Pa \Rightarrow V' \gg u$.

Let us recall that the initial hypotheses (and the experimental conditions) were:

$$Vo \ll c \;;\; v' \ll Vo \quad \text{and} \quad Pa \ll P' \Rightarrow u \ll v'$$

Experiments Performed in the Wind Tunnel at the Research and Study Center of Toulouse (C.E.R.T.)

Choice of experimental apparatus

In order to produce a noiseless airflow around a microphone, we had the choice of two possibilities: (1) move the microphone in the air, or (2) produce an airflow around the microphone, which is held fixed. The first approach corresponds to the one adopted by Bruel and Kjaer; there was only limited interest in following it again, especially since it is open to criticism. In fact, the microphone placed on the "turn-stile" device moves in the ridge it created on previous turns. As for imposing a uniform rectilinear motion, we did not give it any consideration because of obvious technical difficulties. /10

The second solution is to place the microphone in a wind tunnel. However, a wind tunnel produces a considerable amount of noise. Now, since the purpose of our experiments was to attempt to determine the response of a microphone due solely to the flow of air around it, it was necessary to be able to measure the background noise at the position of the microphone that was placed in the path of the wind. But this measurement could not be made in the flow path without being perturbed by it. Thus, we chose to use two microphones, one in the flow path, the other outside, on the hypothesis that the output signal of the latter is a good indication of the background noise within the flow path.

Two similar solutions could, a priori, be adopted:

— Case of a wind tunnel with a closed region of airflow (Figure A)

This solution was not chosen, since microphone 2 would be sensitive to turbulence in the boundary layer. On the other hand, taking account of the dimension of the airflow region, standing waves /11

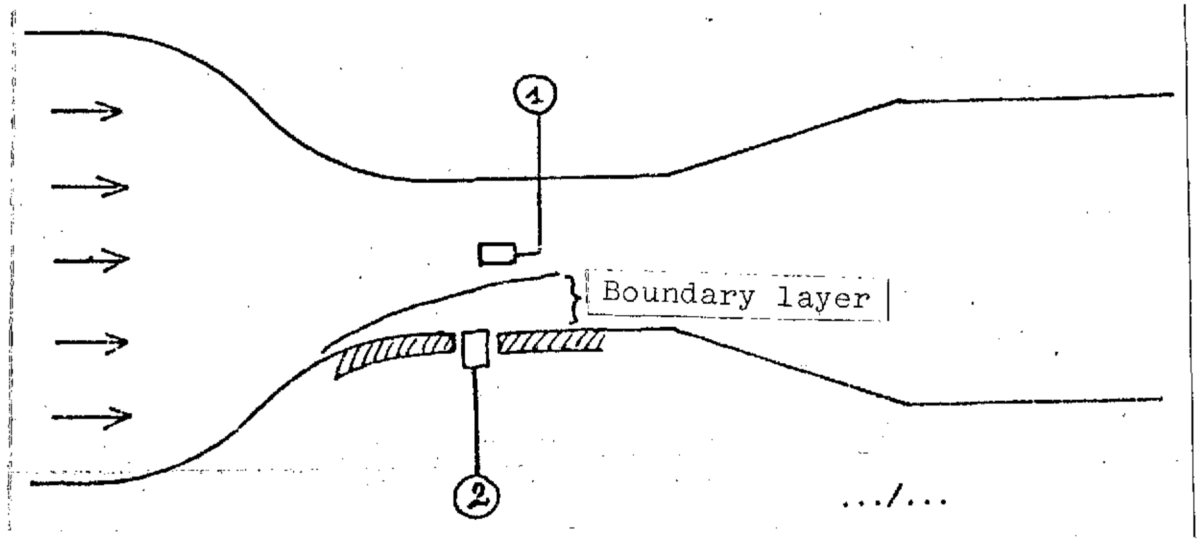


Figure A.

are cause for concern (on this subject, see the interpretation of results).

— Case of a wind tunnel with open region of airflow (Figure B). As we have already stated, at the location of microphone 1 there is a superposition of pressure fields:

— acoustic;
— turbulence associated with upstream motion;
— turbulence due to the presence of the microphone.

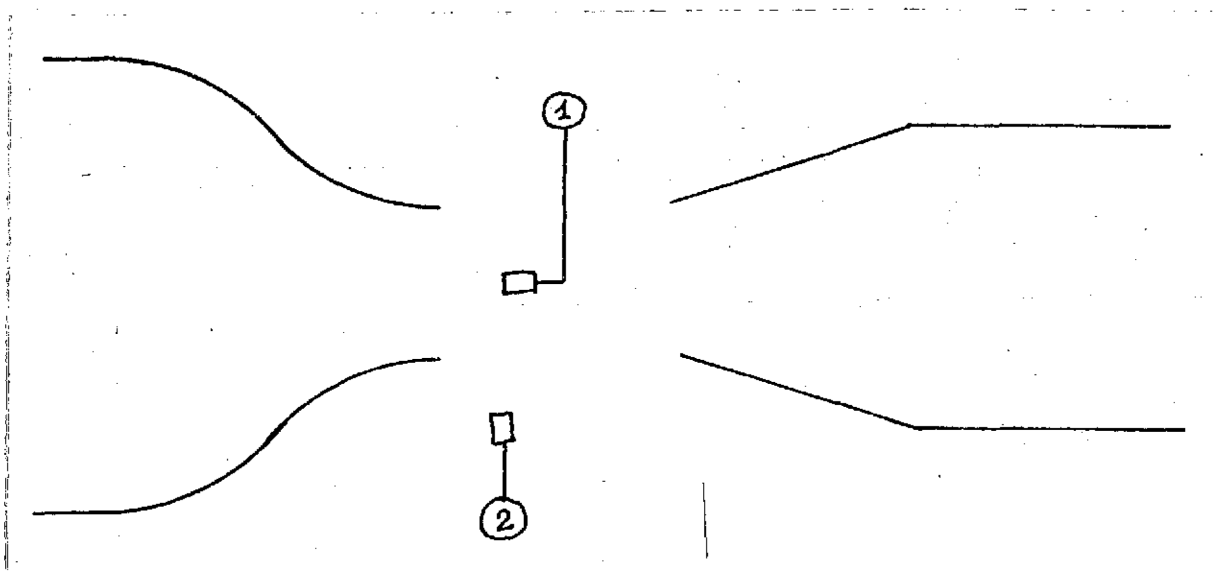


Figure B.

At the location of microphone 2, only the acoustic pressure field is present. To be sure, this acoustic field will not be exactly the same as the one that exists at the location of microphone 1 (we shall take up this problem again in the interpretation of the results), but at least we are sure that microphone 2 will be sensitive only to acoustic pressure, which was not the case before. This is the reason that this solution is the one that was adopted for all the experiments.

Description of the experiments

All the experiments were performed in a IMFL circulating wind tunnel. The airflow region was open and of cross section 0.40 meters on a side. One of the microphones was in the middle of the airflow region, the other outside, about 0.40 meters away.

Experiment 1

Two identical measurement units were used. These comprised two /12
precision Bruel and Kjaer model 2203 portable sonometers, provided with one-inch model 4131 condenser microphones. The filters used were 1/3-octave Bruel and Kjaer filters.

We shall use the index 1 for every element or result corresponding to the measurement unit for which the microphone is placed in the flow path, and the index 2 for every element or result corresponding to the other case. We shall say that unit 1 measures the "total noise", and that unit 2 measures the "background noise" (Figure C).

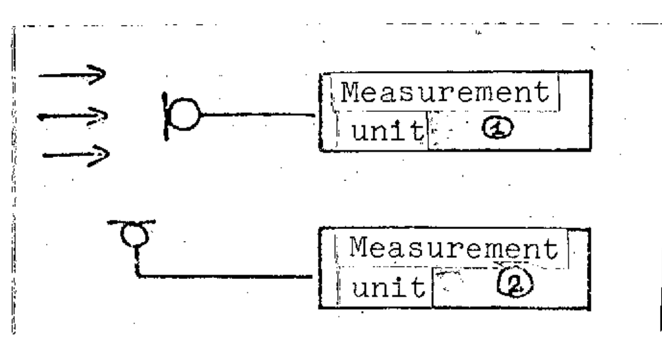


Figure C.

Experiment 2

To determine the turbulence level of the flow before the introduction therein of the microphone, we have used a constant temperature, hot wire anemometer (DISA model 55 M01) and a "low-pass, high-pass" adjustable filter (DISA model 55 D26).

To allow a comparison with the results of Nakamura, we have carried out measurements with three Bruel and Kjaer microphones, of diameter:

— one inch (4131)
— one-half inch (4134)
— one-quarter inch (4136)

Analysis of results

To shorten the notation, we henceforth call P_a (P') the acoustic (turbulent) pressure, while $P_a(t)$ [$P'(t)$] denotes the instantaneous effective value of acoustic [turbulent] pressure variations with respect to the average pressure.

The reading of the sonometer (1) gives the pressure level N_1, which is related to pressure P_1 by: /13

$$N_1 = 10 \log_{10} \left(\frac{P_1}{P_0}\right)^2 \Longleftrightarrow \left(\frac{P_1}{P_0}\right)^2 = 10^{N_1/10}$$

The diaphragm is excited by the pressure $P_1(t)$, and $P_1(t) = P'(t) + P_a(t)$. For the quadratic detector, we can write $P_1^2(t) = (P'(t) + P_a(t))^2$. Finally, for the integrator, we obtain:

$$\overline{P_1^2(t)} = P_1^2 = \overline{[P'(t)]^2} + \overline{[P_a(t)]^2} + 2\,\overline{P'(t)\,P_a(t)}$$

Suppose, so as to be able to take further advantage of the results, that $P'(t)$ and $P_a(t)$ are uncorrelated (which is doubtless not rigorously true); in this case, we can write:

$$\overline{P'(t) \cdot P_a(t)} = 0 \quad \Rightarrow$$

$$P_1^2 = P'^2 + P_a^2 \quad \Rightarrow \quad N_1 = 10 \log_{10} \left(\frac{P'^2 + P_a^2}{P_0^2} \right)$$

As for the microphone (2), it is excited by the pressure P_2 corresponding to the pressure level N_2. If we make the hypothesis $P_2 = P_a$, we then deduce:

$$P1^2 = P'^2 + P_2^2 \Rightarrow P'^2 = P1^2 - P2^2$$

$$\frac{P'^2}{P0^2} = 10^{N1/10} - 10^{N2/10}$$

$$N' = 10 \log \frac{P'^2}{P0^2} = 10 \log \left[10^{N1/10} - 10^{N2/10} \right]$$

N' is the level one would read on the sonometer (1) if there were no acoustic background noise, and if the hypotheses we have made were justified.

Experiment 1

In this series, we have carried out, for several velocities, an analysis by 1/3 octaves of the "total noise" and of the "background noise". We have then removed the "background noise" from the "total noise", as we indicated above, and we have thus obtained the presumed response of a microphone to noiseless airflow.

Figure 10 shows the results obtained for a velocity of 36 km/hr with a one-inch microphone, and the corresponding results found by Bruel and Kjaer. Figure 11 is similar, but

Figure 11 is similar, but for a velocity of 46.5 km/hr. /14

What is immediately apparent in Figure 10 is that the results of Bruel and Kjaer and our own are in close agreement up to about 250 Hz. But beyond this frequency, while for Bruel and Kjaer the

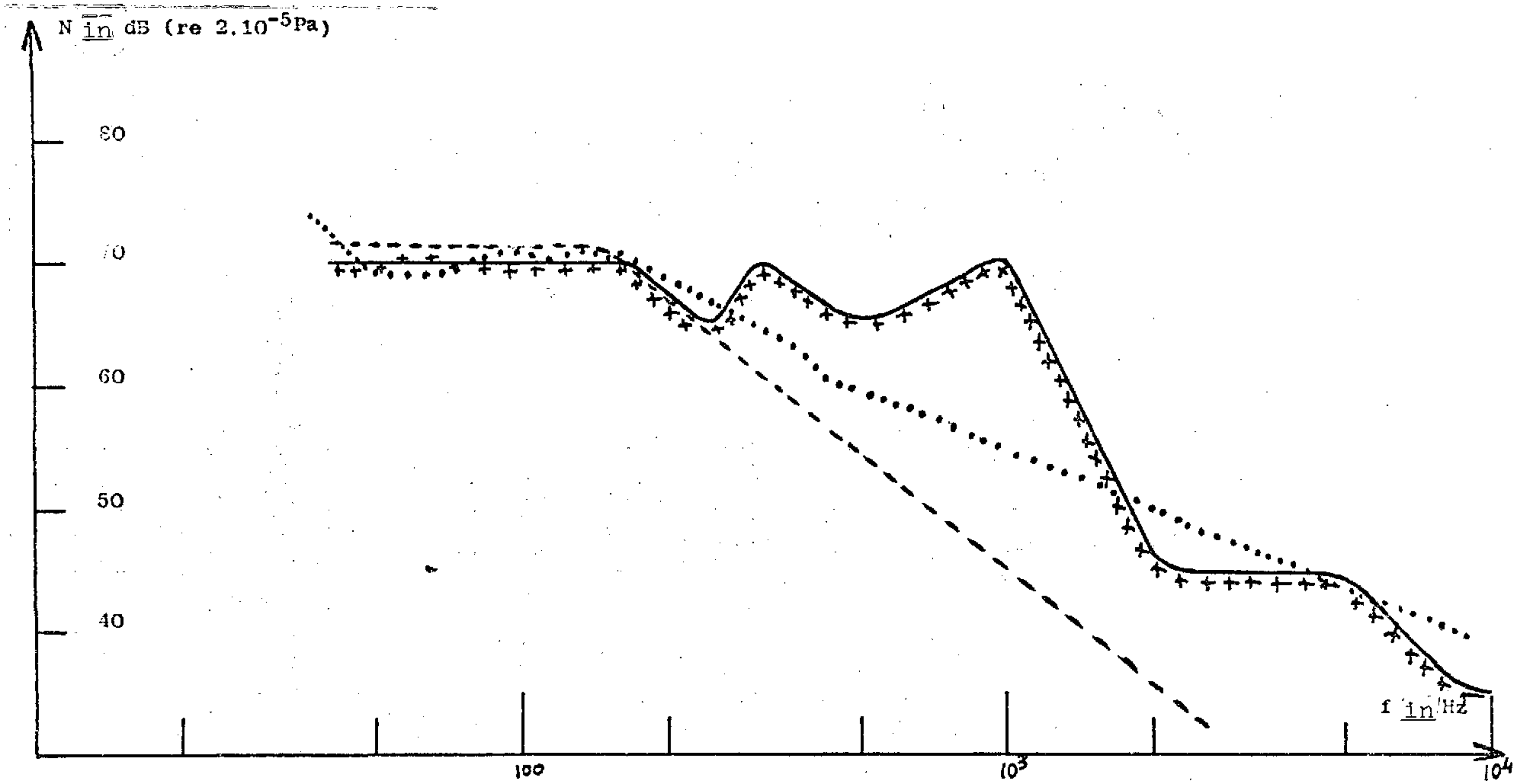


Figure 10. One-inch Bruel and Kjaer model 4131 microphone — mean flow velocity: V_0 = 36 km/hr:

----- — response according to Bruel and Kjaer with a 1-inch microphone without a protective grid; ····· — response according to Bruel and Kjaer with a 1-inch microphone with its protective grid; ——— — our response for a microphone without grid; +++++ — our response for a microphone with grid

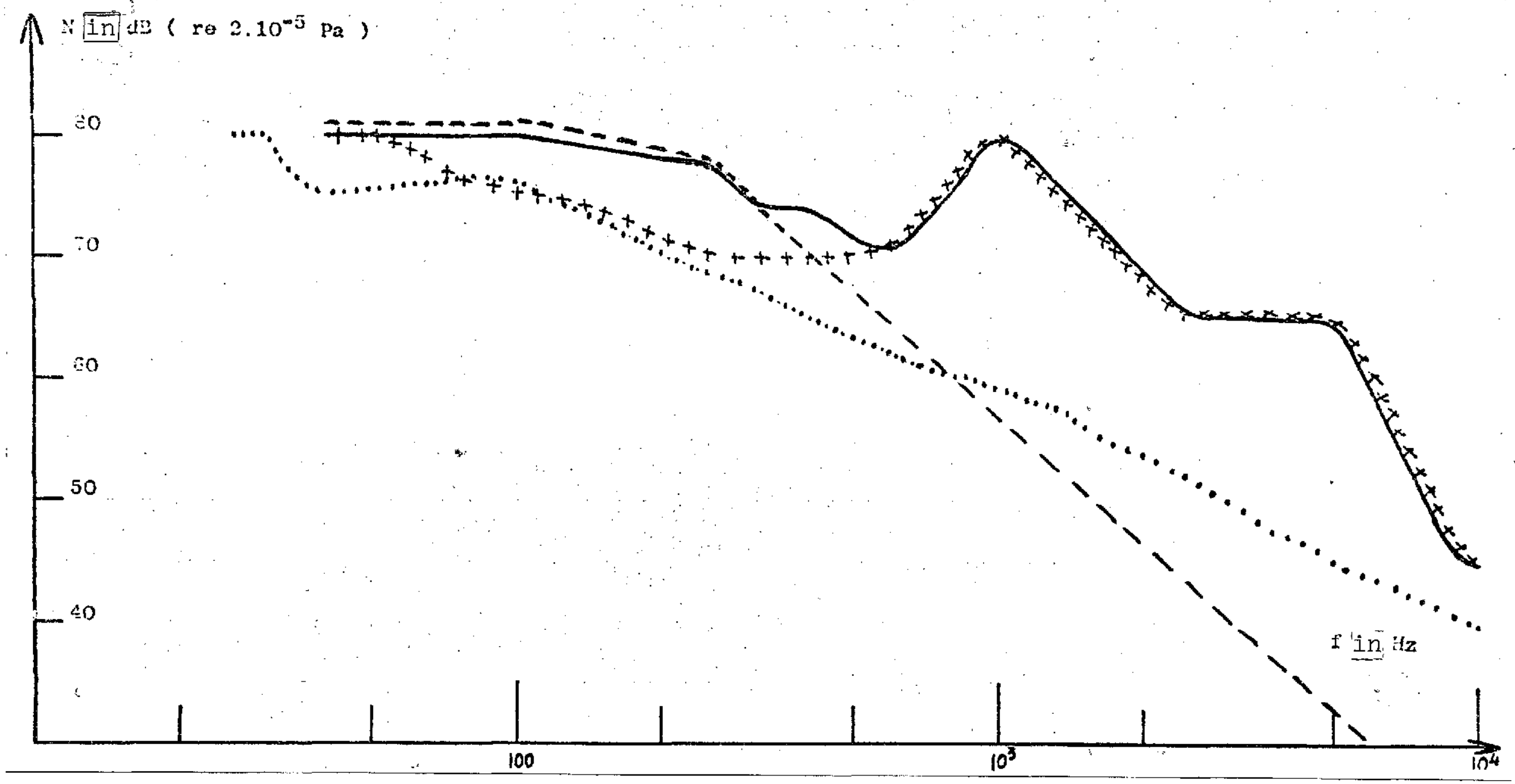


Figure 11. One-inch Bruel and Kjaer model 4131 microphone — mean flow velocity: V_0 = 46 km/hr:

----- — response according to Bruel and Kjaer for a microphone without its protective grid; ····· — response according to Bruel and Kjaer for a microphone with its protective grid; ——— — our response for a microphone without grid; +++++ — our response for a microphone with grid responses of the microphone with and without the grid diverge from each other, we, on the other hand, find no appreciable difference.

Inspection of Figure 11 shows us that our results and those of Bruel and Kjaer are once again comparable up to about 300 Hz. As before, beyond this frequency we do not find any difference between the response of the microphone with and without the grid.

We may deduce from these observations that the hypotheses made above are justified, at the velocities being considered, for frequencies below 250 - 300 Hz. We can also note the presence of a "peak" at about 1000 Hz. This, it seems, must reflect a resonance of the wind tunnel, because we have encountered it in all segments of our work. We have also noticed that if two of the four sides of the airflow region are closed, the feature at 1000 Hz is increased by about 6 dB, which seems to be indicative of a resonance. Finally, it should be remarked that the dimension of the airflow region corresponds approximately to the wavelength at 1000 Hz.

Secondly, we have summed, for each velocity, the levels contained in each 1/3 octave, and we have thus obtained the total level in the bandwidth 22.4 Hz - 22,400 Hz. We have shown in Figure 12, as a function of velocity (expressed in km/hr), the total level (expressed in dB — in the bandwidth 22.4 Hz - 22,400 Hz) obtained with a one-inch microphone with its protective grid. On the same curve, the points obtained by Bruel and Kjaer are included for the sake of comparison.

In curve 13, we notice that there is no appreciable difference between the total level (in the frequency band 22.4 Hz - 22,400 Hz) obtained for a microphone with and without its grid, while Bruel and Kjaer found some differences above 50 km/hr.

We have determined that despite very clear spectral differences between the results of Bruel and Kjaer and our own, there is no appreciable distinction in the integrated results.

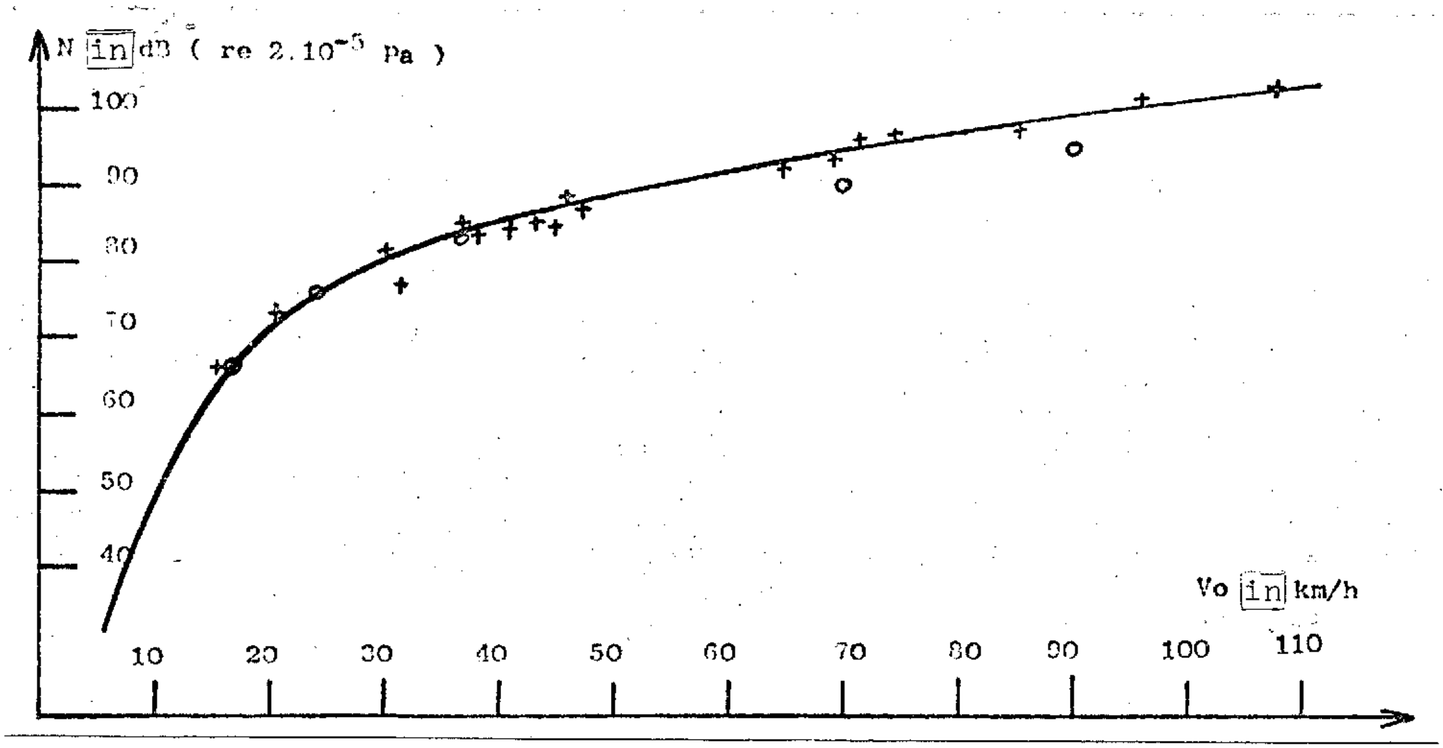


Figure 12. Bruel and Kjaer model 4131 microphone, with grid:
+ — experimental points found at the Research and Study center of Toulouse; o — experimental points found by Bruel and Kjaer

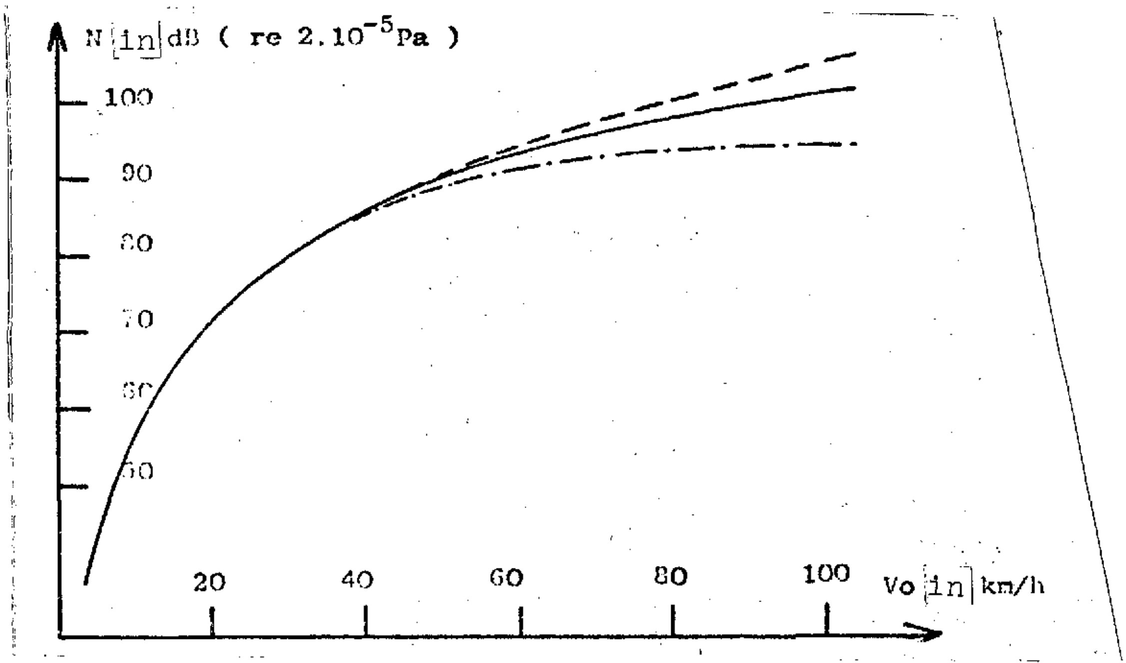


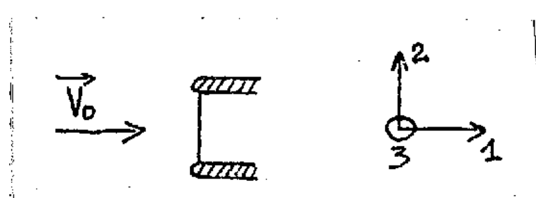
Figure 13. Bruel and Kjaer model 4131 microphone: ——— — response found at the Research and Study Center of Toulouse with or without the grid; ----- — response found by Bruel and Kjaer for the microphone without the grid; —·—·— — response found by Bruel and Kjaer for the microphone with grid

This would not surprise the metrologist, since every integrated level measurement is obtained at a price, namely, the loss of important spectral information.

Experiment 2

The analyses by octave thirds carried out on the signal produced by the one inch, one-half inch, and one-quarter inch microphones have been handled in the same manner as before. /18

As for the response of the hot-wire anemometer, it depends only on the component of velocity normal to the wire.



Let us consider, then, a filament perpendicular to the average flow velocity V_0, as was the case in the experiment. We can write:

$$\vec{Vo} = \begin{vmatrix} Vo + w_1' \\ w_2' \\ w_3' \end{vmatrix}$$

The component normal to the wire, V_n, is written:

$$Vn = \sqrt{(Vo + w_1')^2 + w_3'^2}$$

$$Vn = Vo \sqrt{1 + 2\frac{w_1'}{Vo} + \frac{w_1'^2}{Vo^2} + \frac{w_3'^2}{Vo^2}}$$

$\frac{w_1'^2}{Vo^2}$ and $\frac{w_3'^2}{Vo^2}$ may be neglected, and there remains:

$$Vn = Vo \sqrt{1 + \frac{2 w_1'}{Vo}} \Rightarrow \boxed{Vn \neq Vo + w_1'}$$

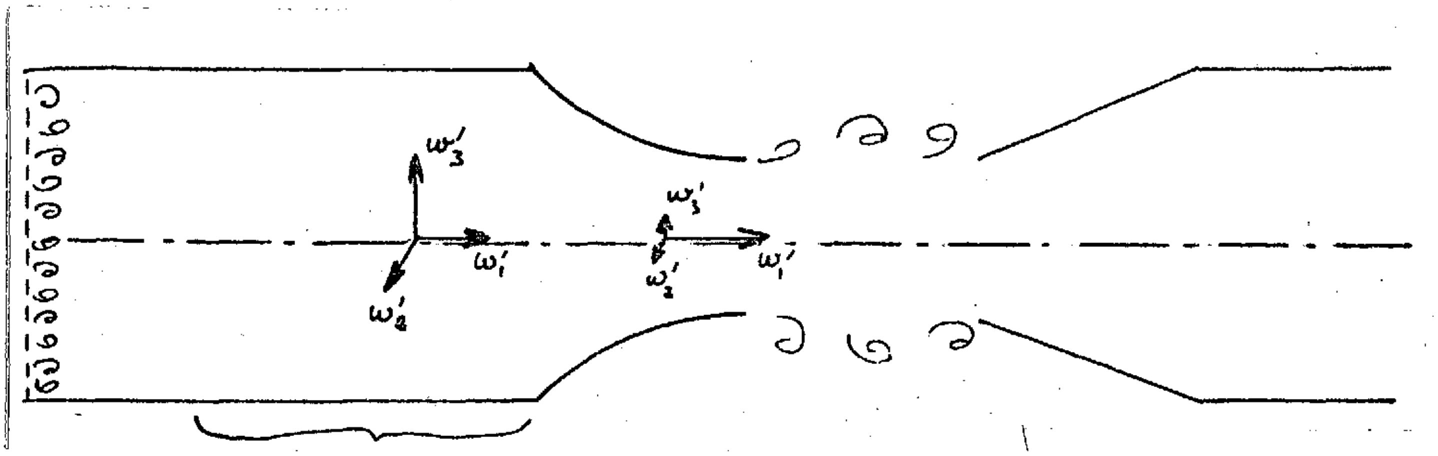
In this experiment, we have thus measured only the fluctuations w_1' in the direction of V_0. It would have been pr...

It would have been preferable to be able to measure w_2' and w_3', but we can nevertheless make a hypothesis relating w_1', w_2', w_3':

Between the grid and the constricted region (Figure E), there /19
is developed a homogeneous isotropic turbulence. The principal effect of the constriction is to accelerate the flow; a secondary effect is to "squeeze together" the transverse velocity components. It is thus reasonable to suppose that:

$$w_2' \simeq w_3' \ll w_1'$$

therefore $w' \neq w_1'$.



Homogeneous isotropic turbulence

Figure E.

This velocity fluctuation w', measured at the hot-wire anemometer, may be written:

$$w' = v' + u$$

where v' is the turbulent velocity fluctuation, and u is the acoustic velocity fluctuation.

If we wish now to translate these velocity fluctuations into pressure fluctuations, we must write:

$$p' = \rho \overline{V_0 v'} + \rho c u$$

We therefore again find ourselves facing the same problem that we had before, to wit: we must be in a position to account for the turbulence as well as the acoustics. To do that, we remain faithful to the same method, that is, we have assumed that the noise measured outside the airflow region was a good representation of what existed inside. We have thus found that the term $\rho c u$ was negligible compared with the term $\rho V_0 v'$. We thus obtain the turbulent pressure fluctuations that excite the membrane of the microphone, which will translate into pressure level according to the relationship:

$$N' = 10 \log \left(\frac{p'}{p_0} \right)^2$$

where $p_0 = 2.10^{-5}$ Pa.

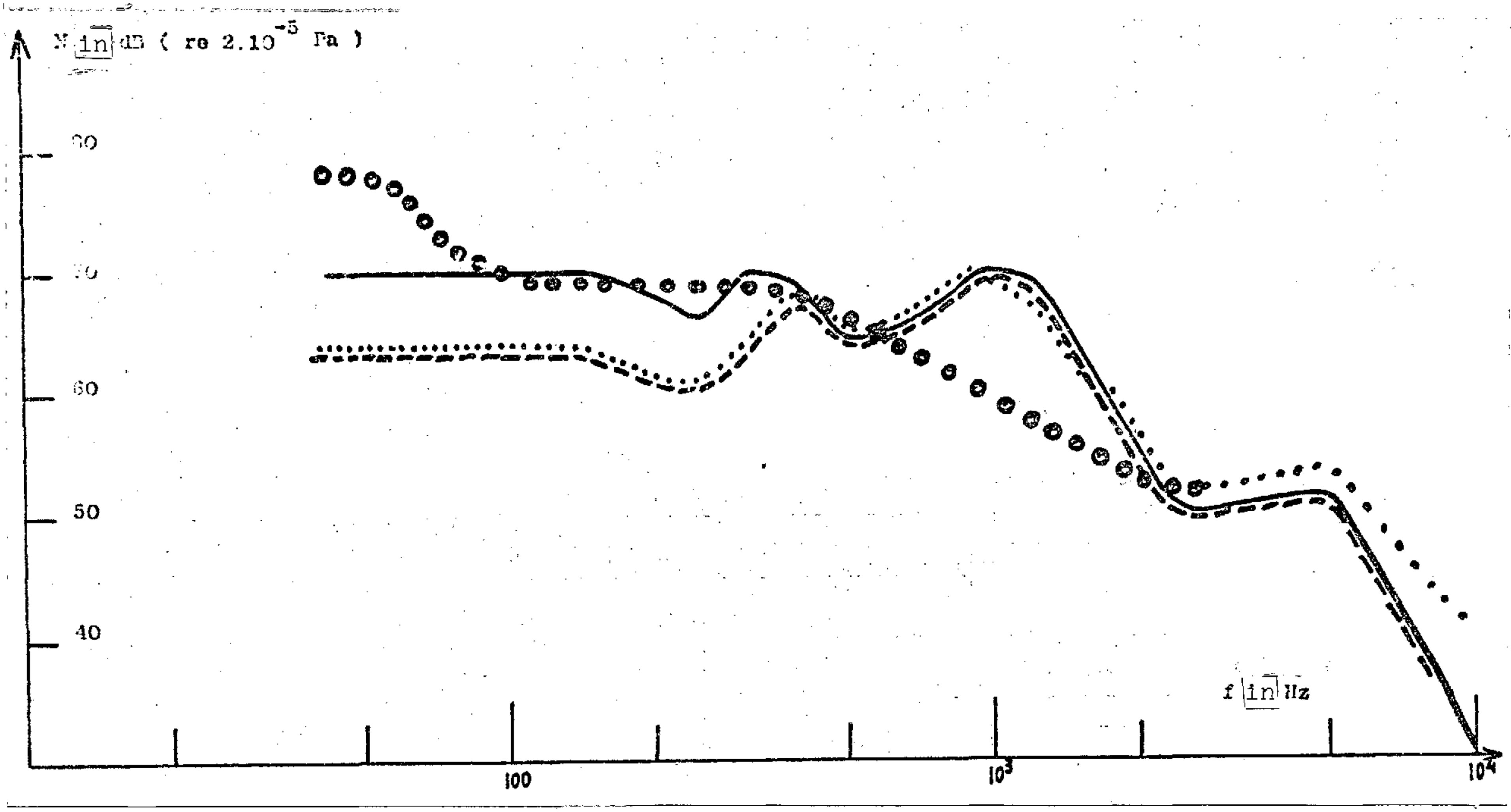


Figure 14: Mean flow velocity: V_0 = 36 km/hr.

ooooo — pressure fluctuations calculated on the basis of measured values of velocity fluctuations through the relationship $P' = V_0 v'$; ——— — level measured with a 1-inch Bruel and Kjaer model 4131 microphone without grid; ····· — level measured with a one-half-inch Bruel and Kjaer model 4134 microphone without grid; ----- — level measured with a one-quarter-inch Bruel and Kjaer model 4136 microphone without grid

In Figure 14, we have shown the high pressure levels (for a velocity of 10 m/s) obtained with 1-inch, 1/2-inch, and 1/4-inch microphones. We have also indicated the pressure level calculated on the basis of the measurement of the velocity fluctuations. /21

While the responses of the 1/2-inch and 1/4-inch microphones are in perfect agreement with each other over the entire range of the frequencies studied, the response of the 1-inch microphone is different in the low frequencies, and we are at a loss to explain this fact.

On the other hand, it may be determined that the pressure level calculated on the basis of the measurement of velocity fluctuations corresponds roughly to the level indicated by the microphones, and that there is no evidence whatsoever of the cutoff frequencies that were a feature of the work of Nakamura.

This lack of agreement with Nakamura's work could be related to the fact that the noise measured outside the region of airflow differs from that actually existing in the flow path.

Conclusions and Outlook for the Future

It is now readily appreciated that the problem in making noise measurements within the flow region relates to the fact that a transducer (whether for velocity or pressure) is incapable of differentiating fluctuations due to turbulence from those of acoustic origin. /22

In order to calculate the noise within the flow region, we have formulated a crude hypothesis. Nevertheless, the results obtained are encouraging for the low frequencies, and this prompts us to pursue our efforts along the same lines.

To this end, we intend to take advantage of the following idea: the acoustic pressure and the turbulent pressure are of the same order of magnitude, and if we wish to make the turbulent pressure negligible compared with the acoustic pressure, we can either reduce the turbulent pressure or, alternatively, increase the acoustic pressure. It is this latter possibility that we hope to exploit in order to improve the method of estimating the noise within the flow region.

Let us suppose that, for given values of flow velocity and frequency, the output signal of the microphone placed in the flow indicates a pressure level N_1 dB. If, by means of loudspeakers located at the position of the principal sound sources (a motor, for example), we create an additional noise such as would exist in the flow (which will have to be maintained at the same velocity as before) at a level $N_1' = (N_1 + 20)$ dB, we are then sure that this measurement is no longer affected by turbulence and that it corresponds solely to acoustic pressure in the flow. Let us simultaneously make a noise measurement at an exterior point. We shall find a level N_2' which will, as we have seen before, in general be different from N_1'. We can write:

$$N'_1 = N'_2 + N_C$$

where N_C represents the term (that we have just determined) by which it is necessary to correct the exterior level measurement to obtain the interior level.

If we turn off the loudspeakers (and assuming that they were judiciously positioned), we can hope that the correction term N_C will remain approximately the same, and that the noise measurement at the same exterior point, corrected by N_C, will allow us to estimate the acoustic pressure level with sufficient accuracy in the interior region of the flow. /23

Finally, as a check on this method, we can try to separate the acoustic fluctuations from those due to turbulence by taking account of the fact that the former propagate at the speed of sound, while the latter are carried along by the fluid at a velocity roughly equal to that of the mean flow. Thus, if we make two simultaneous measurements at two points along the axis of flow separated by a distance l, we will find the same signals at the two points but with a time delay τ, which will be:

$$\tau = \frac{l}{c} \quad \text{in the case of acoustic fluctuations;}$$

$$\tau = \frac{l}{V_o} \quad \text{in the case of turbulent fluctuations.}$$

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